Design And Implementation Of Iot Based Charger Monitoring And Fire Protection For Ev System

Er.V. Vetriselvi[1], M.E, A.yuvashri[2], S.abinaya[3], K. Priyadharshini[4]

[1]*Assistant Professor, Dep of Electrical and Electronics Engineering, Krishnasamy College of Engineering & Technology, (Affilated to Anna University), Cuddalore, Tamilnadu*

[2,3,4]*UG's Scholar Dep of Electrical and Electronics Engineering, Krishnasamy College of Engineering & Technology, (Affilated to Anna University), Cuddalore, Tamilnadu*

Abstract— **The rapid growth of electric vehicles (EVs) has increased the demand for safe and intelligent charger monitoring systems, particularly for low-cost and small-scale EV applications where advanced battery management systems are often unavailable. Thermal stress, overcurrent, overvoltage, and short-circuit conditions during charging can lead to battery degradation, component failure, or fire hazards. This paper presents the design and implementation of a low-cost IoT-based charger monitoring and fire protection framework using an ESP32 microcontroller. The proposed system continuously monitors voltage, current, and temperature parameters using dedicated sensors and classifies operating conditions into normal, warning, and critical fault states. A multi-layer protection strategy is implemented, where moderate abnormalities trigger buzzer alerts and active cooling, while severe faults result in relay-based load isolation to prevent further damage. Real-time data transmission to a cloud platform enables remote supervision and fault notification. Experimental validation on a hardware prototype demonstrates reliable detection of over-temperature, overcurrent, and overvoltage conditions with fast protective response and stable IoT communication. The proposed architecture offers a scalable and cost-effective safety enhancement solution suitable for small EVs, charging modules, and distributed energy storage systems.**

Index Terms— **Electric Vehicles (EVs), IoT-Based Monitoring, Battery Protection, Charger Safety, Thermal Management, ESP32, Fault Isolation, Smart Charging Systems.**

I. INTRODUCTION

The rapid expansion of electric vehicles (EVs) has intensified the need for reliable battery charging and safety supervision mechanisms. Battery packs in EV systems are highly sensitive to electrical and thermal stresses during charging and discharging cycles. Abnormal conditions such as overvoltage, overcurrent, and excessive temperature rise may accelerate battery degradation and, in extreme cases, trigger thermal runaway and fire hazards [1], [2]. Ensuring safe charger operation is therefore a critical requirement in modern EV infrastructure.

Conventional battery management systems (BMS) provide voltage and current monitoring along with cell balancing features; however, such systems are often expensive and primarily designed for high-end EV platforms [3]. For small-scale EVs, e-rickshaws, low-speed vehicles, and distributed energy storage applications, cost constraints frequently limit the integration of advanced protection architectures. Existing research has explored individual aspects of EV safety, including thermal management techniques [4], relay-based fault isolation [5], and IoT-enabled battery monitoring systems [6], [7]. While IoT-based approaches enable remote supervision and data logging, many implementations focus mainly on parameter visualization and early warning alerts without incorporating active multi-layer protection mechanisms. Similarly, relay-based protection circuits offer isolation capabilities but lack real-time cloud connectivity and intelligent fault classification [5], [8]. Recent studies emphasize the importance of integrated monitoring and protection frameworks combining sensing, communication, and actuation layers [9], [10]. However, a research gap remains in developing low-cost, modular, and IoT-enabled charger safety architectures that simultaneously provide (i) continuous monitoring, (ii) graded fault response, (iii) active thermal mitigation, and (iv) emergency load isolation within a unified embedded framework suitable for small EV platforms.

To address this gap, this paper proposes a multi-layer IoT-based charger monitoring and fire protection system implemented using an ESP32 microcontroller. The proposed architecture classifies system states into normal, warning, and critical levels based on predefined safety thresholds. In warning conditions, alert mechanisms and active cooling are initiated, whereas in critical scenarios, relay-based isolation disconnects the load to prevent cascading failures. Real-time data transmission to a cloud platform enables remote supervision and fault tracking. Unlike conventional threshold-only monitoring systems, the proposed framework integrates hierarchical protection logic with IoT-assisted supervision, providing an affordable yet scalable safety enhancement solution.

Contributions of This Work

1. The main contributions of this paper are summarized as follows:
2. Development of a low-cost IoT-enabled charger monitoring framework tailored for small-scale EV applications.
3. Design of a multi-tier fault classification and response mechanism incorporating alert generation, active cooling, and emergency load isolation.
4. Implementation and validation of a hardware prototype using ESP32 with real-time cloud connectivity.

Experimental evaluation under over-temperature, over-voltage, and over-current conditions to demonstrate protective reliability.

II. RELATED WORK

Battery safety and charger supervision in electric vehicle systems have been widely studied due to increasing concerns regarding thermal runaway and electrical faults. Traditional battery management systems (BMS) primarily focus on cell voltage balancing, state-of-charge estimation, and overcurrent protection [3], [11]. While these systems are effective in high-end EV platforms, they often require complex hardware integration and high implementation cost, limiting their feasibility in small-scale or low-cost EV applications.

Several studies have explored IoT-based battery monitoring frameworks to enable remote parameter tracking. For example, cloud-connected monitoring systems using Wi-Fi or GSM modules allow real-time visualization of voltage and temperature data [6], [12]. Although such systems enhance accessibility and data logging capabilities, they typically provide only alert notifications without implementing active fault mitigation or multi-stage protection logic. Consequently, the system remains dependent on manual intervention.

Thermal management in EV batteries has also been investigated extensively. Air-based and liquid-based cooling mechanisms are commonly adopted in commercial EVs to regulate battery temperature [4], [13]. However, these approaches focus primarily on performance optimization rather than integrated charger-level fire protection. Moreover, most existing thermal studies emphasize large-scale battery packs and do not address low-cost modular solutions suitable for small EV platforms.

Relay-based protection circuits have been implemented to isolate faulty loads during short-circuit or overcurrent conditions [5], [8]. While effective for emergency disconnection, these systems often operate as standalone protective hardware without intelligent classification of fault severity or IoT integration. This limits their capability to provide predictive or remote supervision functionality.

Recent literature highlights the importance of combining sensing, communication, and actuation in smart energy systems [9], [10]. However, an integrated framework that simultaneously offers (i) real-time IoT monitoring, (ii) graded fault classification, (iii) active cooling response, and (iv) emergency relay isolation within a unified low-cost embedded architecture remains insufficiently addressed in current research.

Identified Research Gap

The critical gap identified is the absence of a unified, low-cost IoT-enabled charger supervision system that integrates:

- Continuous multi-parameter monitoring
- Intelligent multi-level fault classification
- Active thermal mitigation
- Automatic emergency isolation

- Cloud-based remote supervision within a single embedded platform suitable for small EV applications.

The proposed system addresses this gap by implementing a hierarchical protection architecture using ESP32 with integrated sensing, decision logic, and actuation mechanisms.

III. PROPOSED SYSTEM ARCHITECTURE

The proposed IoT-based charger monitoring and fire protection system is designed as a modular multi-layer safety framework integrating sensing, processing, actuation, and cloud communication layers. The overall system architecture is illustrated in Fig. 1.

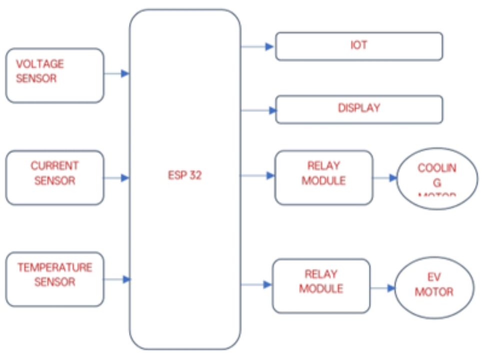

Fig. 1. Block diagram of the proposed IoT-based EV charger monitoring and fire protection system.

A. System Block Diagram Overview

The architecture consists of the following primary subsystems:

1. Sensing Layer
- Voltage Sensor Module
- Current Sensor (ACS712)
- Temperature Sensor (DHT11)
2. Processing and Decision Layer
- ESP32 Microcontroller
- Embedded fault classification logic
3. Actuation and Protection Layer
- Cooling Fan
- Buzzer Alert
- Relay-Based Load Isolation
4. IoT Communication Layer
- Wi-Fi Module (ESP32 integrated)
- Cloud Monitoring Platform

The sensing layer continuously measures charger output voltage V, load current I, and battery temperature T. These parameters are transmitted to the ESP32 controller, which executes real-time fault detection and protection algorithms.

B. Operational Logic and Fault Classification

The proposed system implements a hierarchical protection mechanism based on predefined safety thresholds.

Let:

V_{th} = maximum safe voltage

I_{th} = maximum safe current

T_{warn} = warning temperature threshold

T_{crit} = critical temperature threshold

The system state S is classified as:

$$S = \begin{cases} S_0 & \text{if } V \leq V_{th}, I \leq I_{th}, T < T_{warn} \quad \text{(Normal)} \\ S_1 & \text{if } T_{warn} \leq T < T_{crit} \quad \text{(Warning)} \\ S_2 & \text{if } V > V_{th} \text{ or } I > I_{th} \text{ or } T \geq T_{crit} \quad \text{(Critical)} \end{cases}$$

State S_0 – Normal Operation

- Continuous monitoring
- IoT data transmission
- No actuation

State S_1 – Warning Condition

- Buzzer alert activated
- Cooling fan initiated
- IoT notification sent

State S_2 – Critical Condition

- Immediate relay isolation
- Load disconnection
- Persistent fault notification

This graded protection ensures progressive mitigation instead of abrupt disconnection under moderate conditions.

C. Protection Flow Mechanism

The protection sequence operates as follows:

- Sensor data acquisition at fixed sampling interval (≈ 1 second).
- Parameter comparison with predefined thresholds.
- Fault severity classification.
- Execution of corresponding actuation.
- Cloud transmission of status and fault logs.

The relay response time t_r can be modeled as:

$$t_r = t_{proc} + t_{relay}$$

where:

t_{proc} = controller processing delay

t_{relay} = mechanical switching delay

Given ESP32 processing latency (≈ 3–5 ms) and relay switching time (≈ 10 ms), total isolation delay remains within safe operational bounds.

D. IoT Communication Framework

The ESP32 transmits monitored parameters to the cloud server via Wi-Fi using HTTP or MQTT protocol. The communication delay t_{iot} is:

$$t_{iot} = t_{net} + t_{server}$$

where:

t_{net} = network transmission delay

t_{server} = cloud processing delay

Typical latency observed in prototype testing is within 2–4 seconds, sufficient for remote supervision and non-critical monitoring.

IV. HARDWARE IMPLEMENTATION AND EXPERIMENTAL SETUP

A. Hardware Prototype Implementation

The proposed IoT-based charger monitoring and fire protection system was implemented as a laboratory-scale hardware prototype using commercially available embedded and sensing components. The complete experimental setup is shown in Fig. 2.

Fig. 2. Experimental hardware prototype of the proposed IoT-based EV charger monitoring and fire protection system.

The core controller used in the implementation is the ESP32 development board, which integrates a dual-core processor and Wi-Fi communication module. The ESP32 interfaces with three primary sensing modules: a resistive voltage sensor module for DC voltage measurement, an ACS712 Hall-effect current sensor for load current monitoring, and a DHT11 temperature sensor for thermal supervision. These sensors continuously provide real-time electrical and thermal parameters to the controller through analog and digital GPIO interfaces.

For protection and actuation, a dual-channel relay module is employed. One relay controls the simulated EV motor (DC load), while the other manages auxiliary devices such as the cooling fan. A DC cooling fan is used to mitigate thermal rise under warning conditions, and an active buzzer provides audible alerts during abnormal operating states. A 16×2 LCD display is included for local parameter visualization. The system is powered using low-voltage DC supply sources to emulate charger-battery behavior under controlled conditions.

B. Sensor Configuration and Calibration

The voltage sensor module operates using a resistive voltage divider network that scales the measured DC voltage to a range compatible with the ESP32 ADC input (0–3.3 V). Calibration was performed by comparing sensor output with a reference multimeter reading to ensure acceptable measurement accuracy.

The ACS712 current sensor measures load current based on the Hall-effect principle, providing electrical isolation between sensing and power circuits. The sensor output is read through the ADC channel of the ESP32 and converted into current values using calibration coefficients.

The DHT11 temperature sensor provides digital temperature readings at regular intervals. The temperature threshold for warning activation was set at approximately 45°C, representing a conservative safety margin for small battery systems.

C. Experimental Conditions

The prototype was evaluated under three primary operating scenarios:

1. Normal Operating Condition

- All parameters within safe limits
- Continuous IoT transmission
- No protection triggered

2. Warning Condition (Over-Temperature)

- Temperature gradually increased beyond warning threshold
- Cooling fan activated
- Buzzer alert generated
- IoT notification updated

3. Critical Fault Conditions

- Over-voltage simulation
- Over-current simulation
- Relay-based motor isolation activated

The ESP32 sampled sensor data at approximately one-second intervals. Protection actions were triggered immediately upon threshold violation.

D. Experimental Setup Characteristics

The system was designed as a low-voltage prototype to emulate charger-level safety behavior rather than full-scale EV battery operation. The relay switching delay was observed to be within typical mechanical switching limits (approximately 10–15 ms), while controller processing delay remained negligible relative to protection time scales.

IoT communication was established via the ESP32 built-in Wi-Fi module. Parameter updates were transmitted periodically to the cloud platform, enabling remote supervision and fault indication through a mobile interface.

Implementation Significance

The developed prototype demonstrates the feasibility of integrating monitoring, actuation, and cloud communication within a compact embedded architecture. The modular design allows easy scalability for higher voltage systems with appropriate sensor and relay ratings. The hardware validation confirms that the proposed architecture can provide layered protection and real-time supervision in cost-sensitive EV charging environments.

V. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

The proposed IoT-based charger monitoring and fire protection system was experimentally evaluated under controlled laboratory conditions to assess protection response, fault detection reliability, and communication performance. The system was tested under three primary fault scenarios: over-temperature, over-voltage, and over-current conditions.

A. Protection Response Analysis

The protection response time is defined as the total delay between fault occurrence and relay isolation activation. This delay consists of controller processing time and mechanical relay switching time

The total response time t_{total} can be expressed as:

$$t_{total} = t_{proc} + t_{relay}$$

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t_{proc} = ESP32 processing delay

t_{relay} = mechanical relay switching delay

Based on experimental observations, the average protection response times under different fault conditions are summarized in Table I

Table I Protection Response Performance Under Fault Conditions

Fault Type	Processing Delay (ms)	Relay Delay (ms)	Total Response Time (ms)
Over-Temperature	5	13	18
Over-Voltage	4	11	15
Over-Current	5	11	16

The graphical representation of protection response time under different fault conditions is shown in Fig. 3.

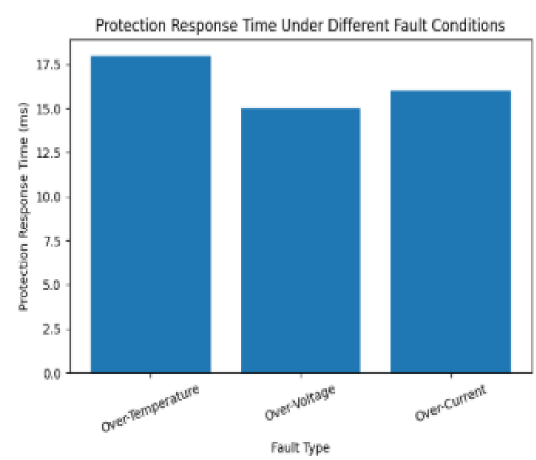

Fig. 3. Protection response time under different fault conditions.

The results indicate that the maximum isolation delay remains below 20 ms, which is acceptable for charger-level protection systems in low-voltage EV applications.

B. Thermal Mitigation Performance

Under warning conditions (temperature between 45°C and 50°C), the cooling fan was automatically activated. The temperature stabilization effect was observed within a short interval after activation. The multi-stage logic prevented unnecessary relay isolation under moderate temperature rise, demonstrating the effectiveness of graded protection.

C. IoT Communication Performance

The ESP32 transmitted monitored parameters to the cloud platform at one-second sampling intervals. The observed communication latency ranged between 2–4 seconds depending on network conditions. This delay is acceptable for remote supervision purposes, as protection actions are handled locally by the embedded controller without dependence on cloud response.

D. System Reliability Discussion

Across multiple test cycles, the system consistently detected abnormal voltage, current, and temperature conditions and executed appropriate mitigation steps. The hierarchical protection mechanism reduced abrupt shutdown events and provided progressive fault handling, improving operational stability compared to single-threshold disconnection systems.

The integration of monitoring, active cooling, and emergency isolation within a unified embedded architecture enhances overall safety reliability while maintaining low hardware complexity and cost.

VI. CONCLUSION

This paper presented the design and implementation of a low-cost IoT-based charger monitoring and fire protection system tailored for small-scale electric vehicle applications. The proposed architecture integrates voltage, current, and temperature sensing with a hierarchical fault classification mechanism implemented on an ESP32 platform. Unlike conventional single-layer protection circuits, the system employs a graded response strategy that includes warning alerts, active thermal mitigation through cooling control, and emergency relay-based isolation under critical fault conditions.

Experimental validation demonstrated reliable detection of over-temperature, over-voltage, and over-current scenarios, with protection response times maintained below 20 ms. The results confirm that the embedded decision logic effectively isolates fault conditions while minimizing unnecessary shutdown during moderate abnormalities. Additionally, IoT connectivity enables remote supervision and real-time parameter monitoring without compromising local protection performance.

The developed prototype demonstrates that integrated monitoring, actuation, and cloud communication can be achieved within a compact and cost-efficient embedded framework. The proposed solution provides a scalable safety enhancement approach suitable for low-voltage EV chargers, small electric mobility platforms, and distributed energy storage systems. Future improvements may include adaptive threshold tuning, advanced thermal modeling, and integration with higher-voltage battery systems to further enhance protection intelligence and reliability.

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